

**7th International Conference on
Physics Opportunities at an ElecTron-Ion Collider
POETIC 7**



Transverse momentum distributions @ EIC

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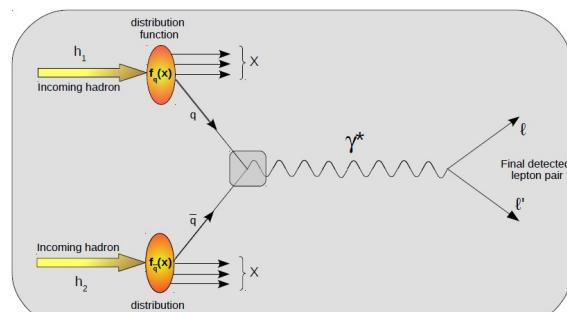
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TAURINENSIS



***Where can we learn about
the 3D structure of matter ?***

Experimental data for TMD studies

Unpolarized and Polarized Drell-Yan scattering



$$\sigma_{Drell-Yan} = f_q(x, k_\perp) \otimes f_{\bar{q}}(x, k_\perp) \otimes \hat{\sigma}^{q\bar{q} \rightarrow \ell^+\ell^-}$$

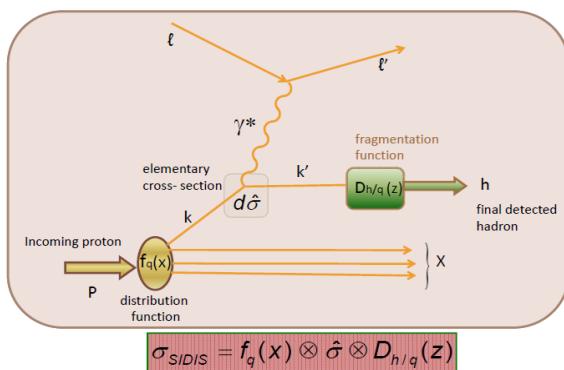
Allows extraction of distribution functions



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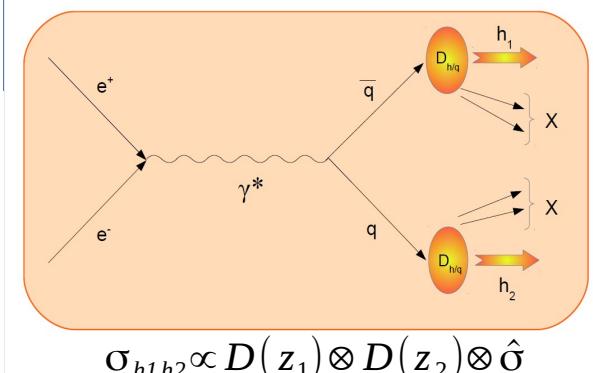


Unpolarized and Polarized SIDIS scattering



Allows extraction of distribution and fragmentation functions

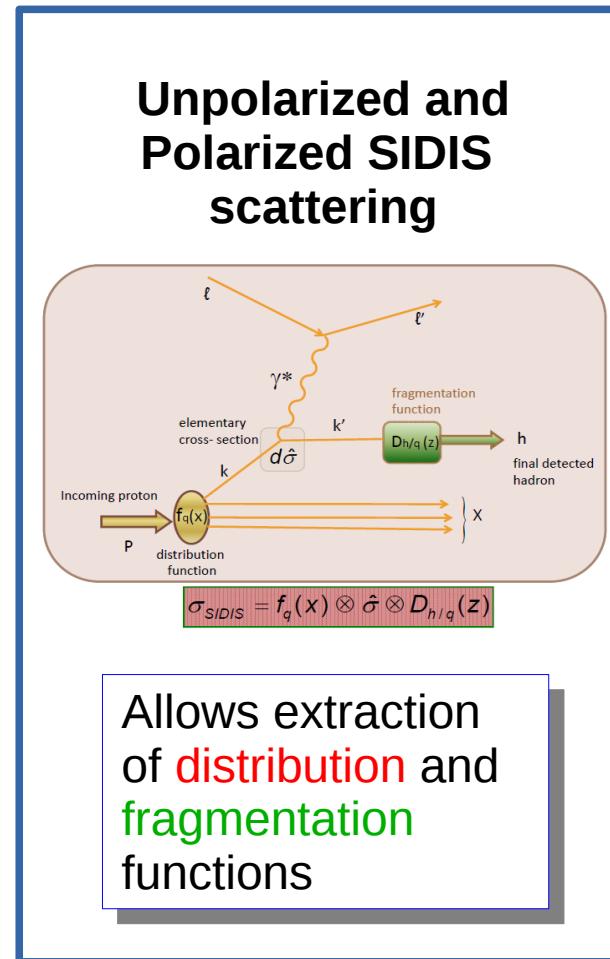
$$e^+ e^- \rightarrow h_1 h_2 X$$



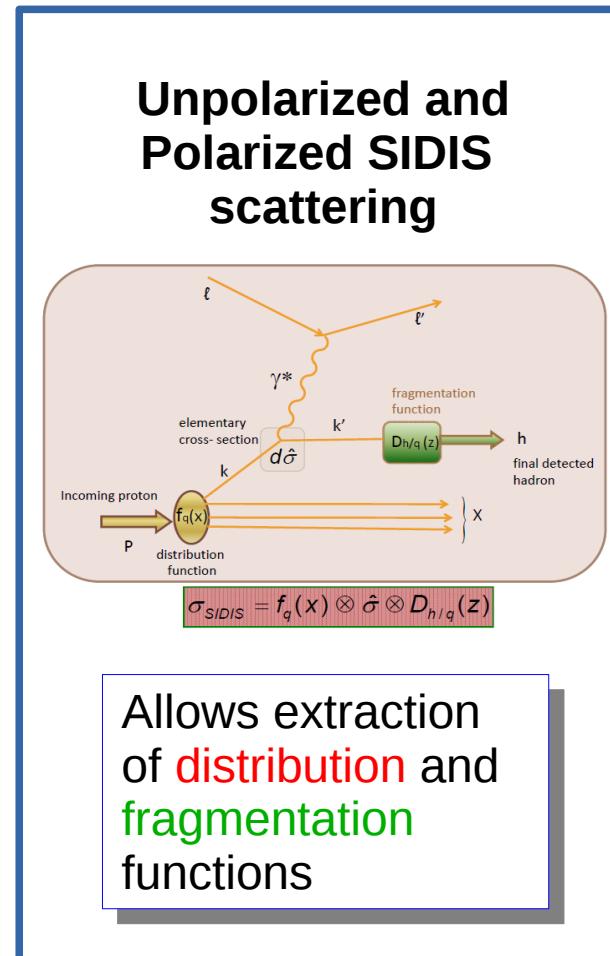
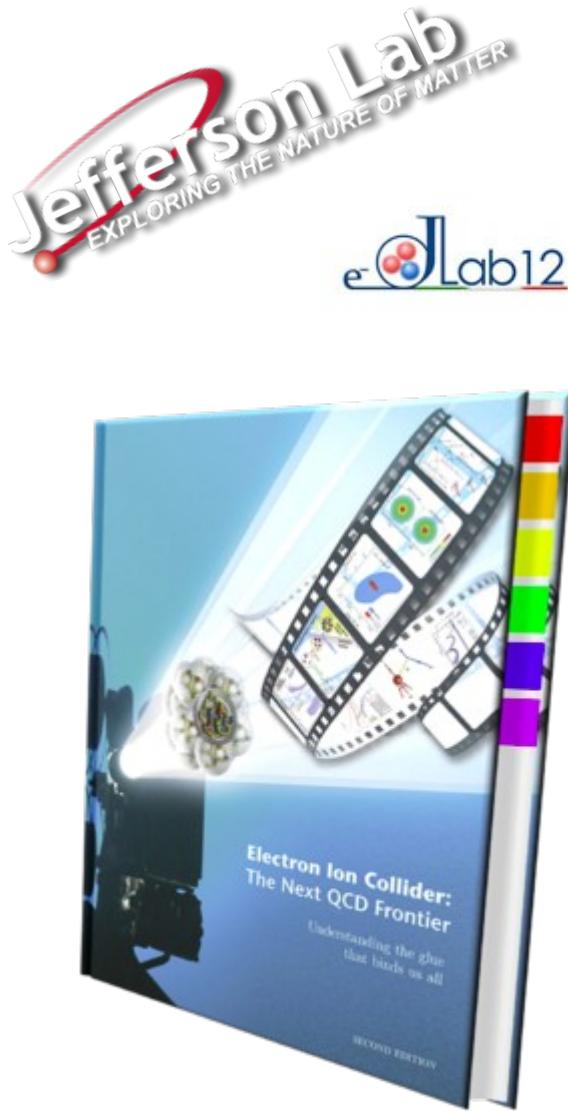
Allows extraction of fragmentation functions



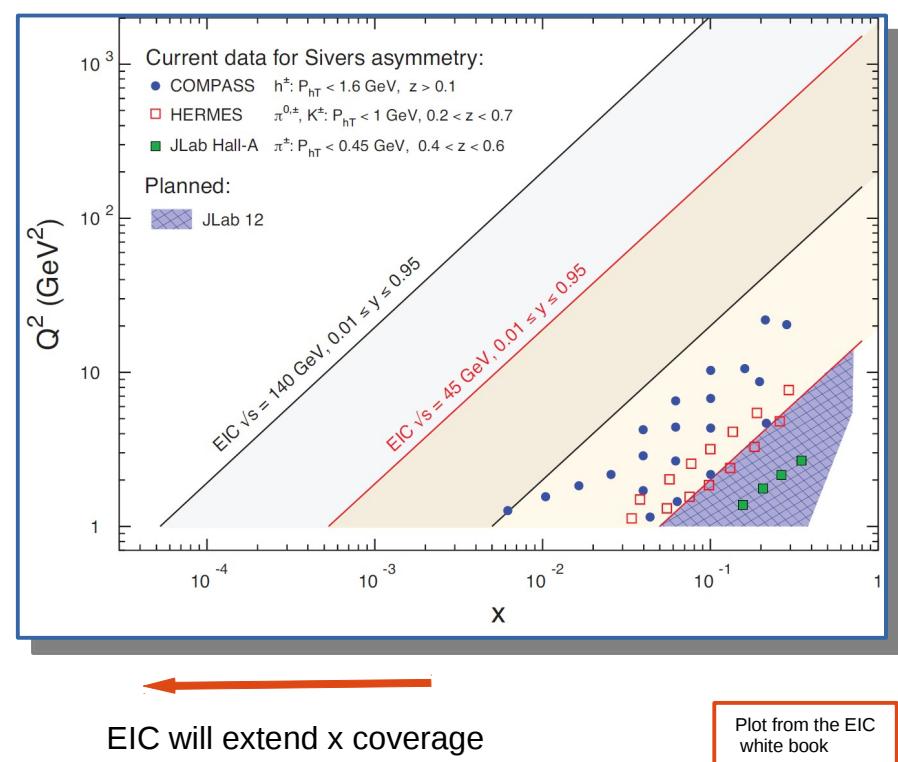
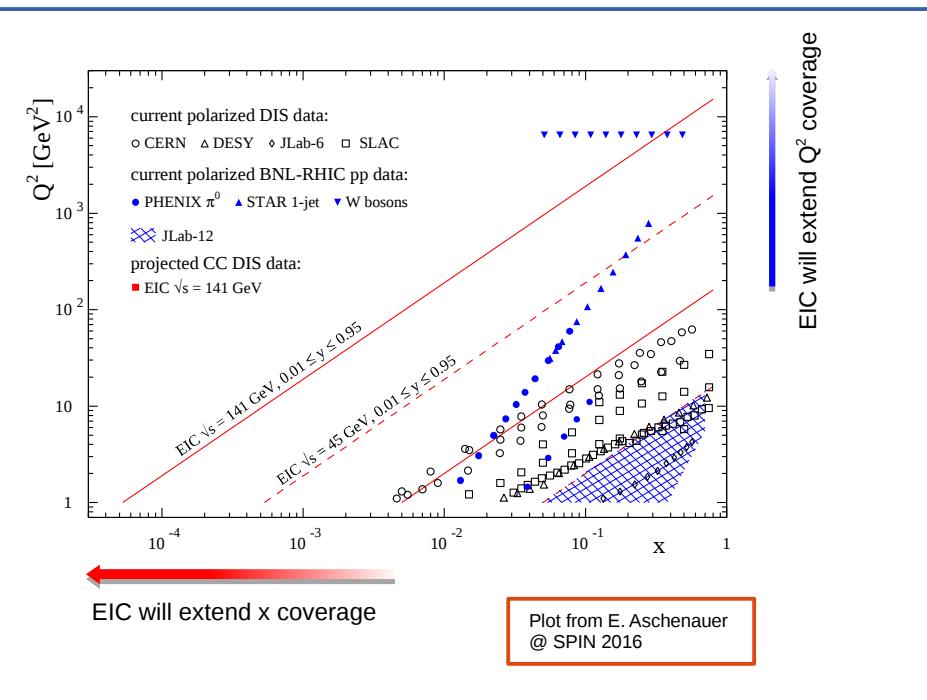
Experimental data for TMS studies



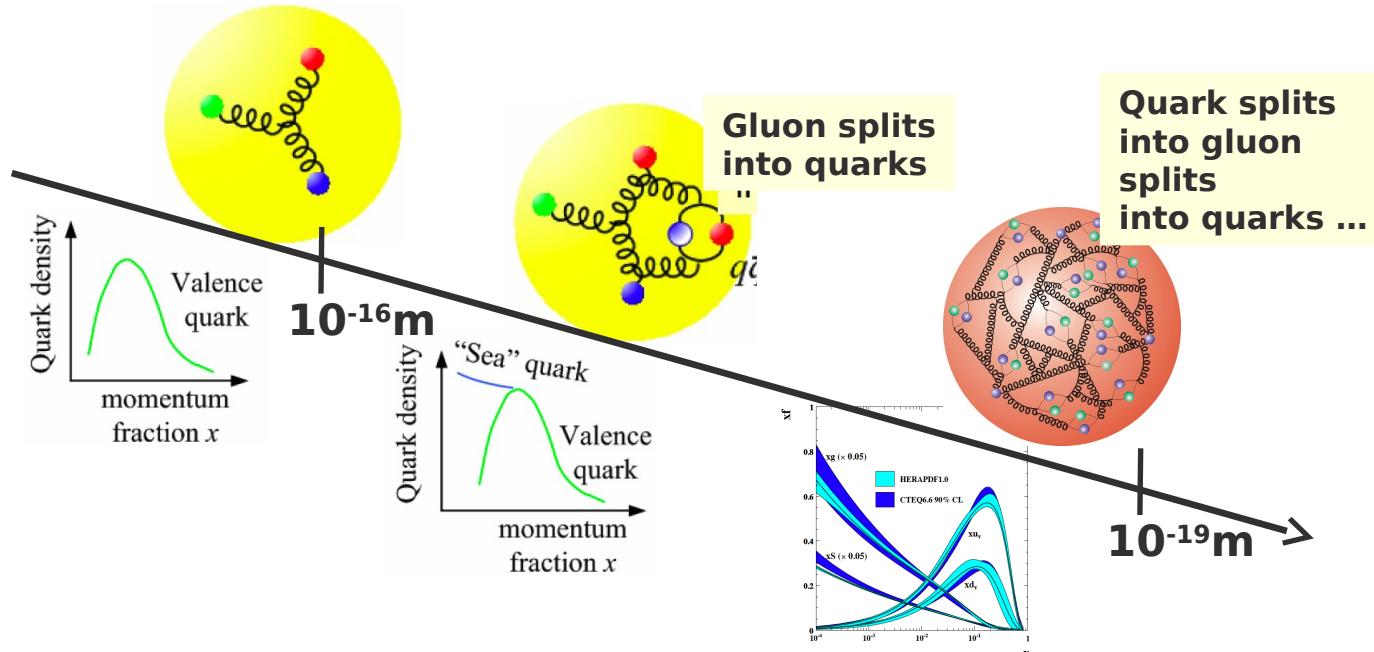
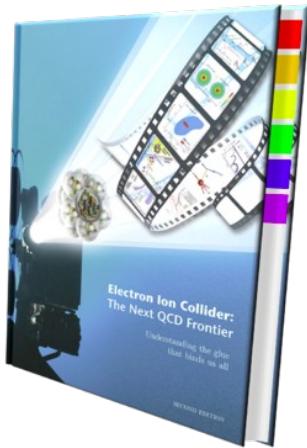
Experimental data for TMS studies



EIC kinematics coverage



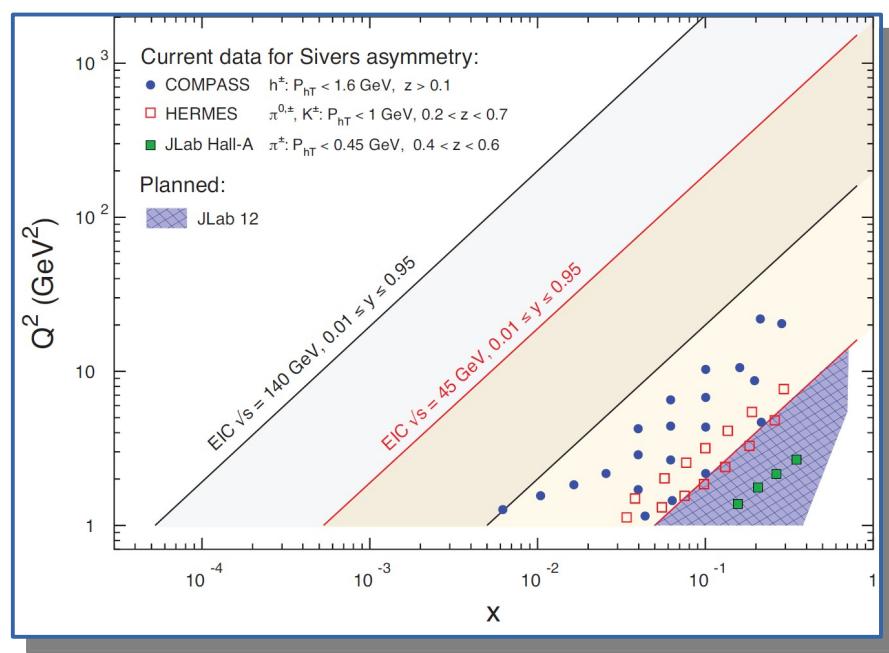
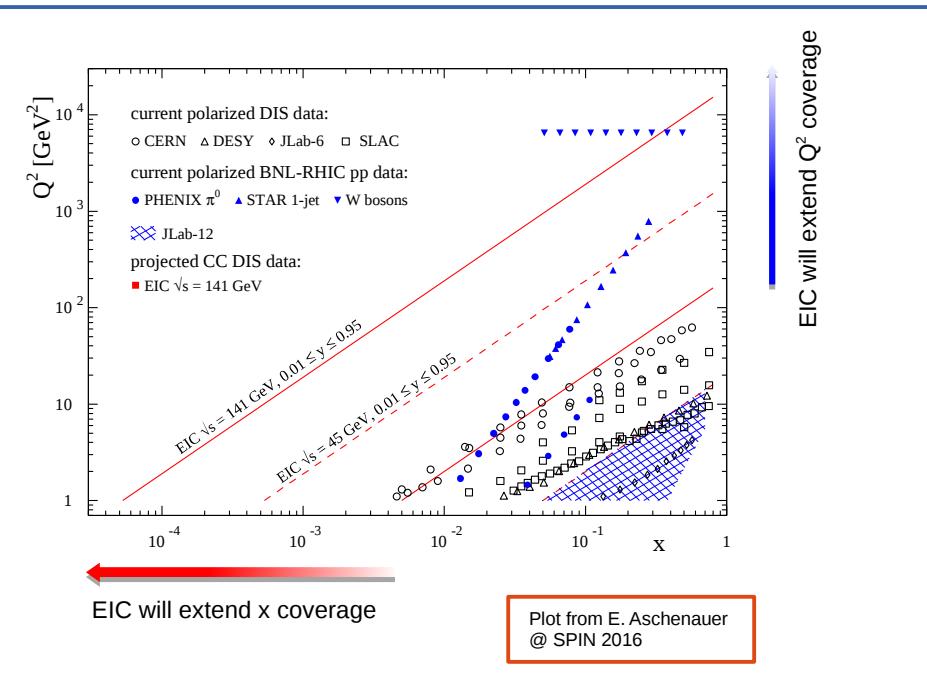
EIC kinematics coverage



Higher \sqrt{s} and Q^2 values will increase resolution

Plot from E. Aschenauer
@ SPIN 2016

EIC kinematics coverage

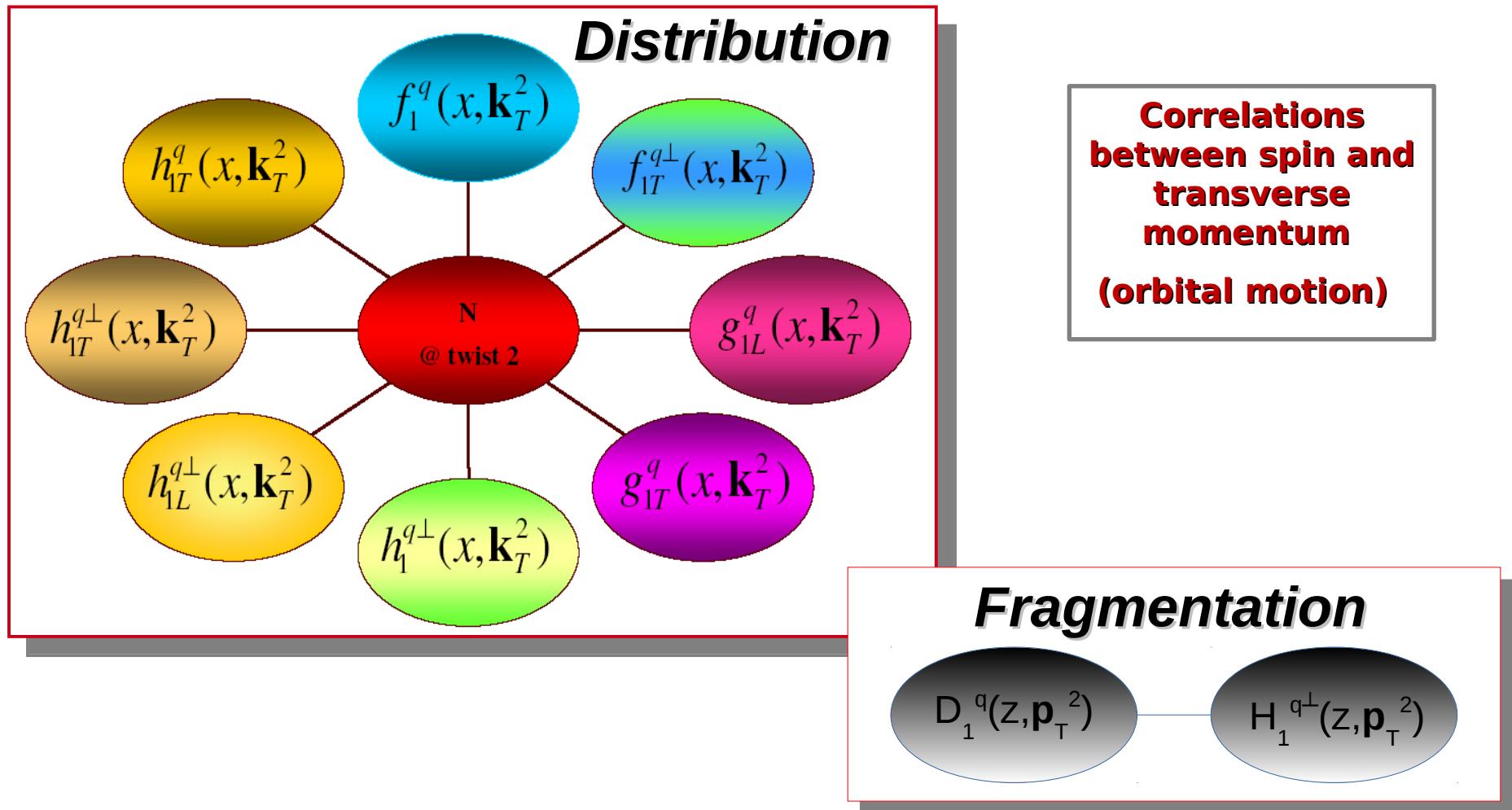


EIC will extend x coverage

Plot from the EIC white book

Transverse momentum dependent parton distribution functions

TMD distribution and fragmentation functions



Extracting unpolarized TMDs from SIDIS data

Extracting the unpolarized TMD Gaussian widths from SIDIS multiplicities

M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261

- Data: **Hermes** (p and d targets, π^+ , π^- , K^+ , K^- production)

2660 data points in (x, z, P_T, Q^2) bins

A. Airapetian et al.,
Phys. Rev. D87
(2013) 074029

Compass (d target, h^+ , h^- production)

18627 data points in (x, z, P_T, Q^2) bins

C. Adolph et al.,
Eur. Phys. J. C73,
2531 (2013)

- Parameterizations:

$$\hat{f}_{q/p}(x, k_\perp; Q) = f_{q/p}(x; Q) \frac{e^{-k_\perp^2/\langle k_\perp^2 \rangle}}{\pi \langle k_\perp^2 \rangle}$$

CTEQ6L (DGLAP evolution)

1 free parameter
(no evolution)

$$D_{h/q}(z, p_\perp) = D_{h/q}(z) \frac{e^{-p_\perp^2/\langle p_\perp^2 \rangle}}{\pi \langle p_\perp^2 \rangle},$$

DSS (DGLAP evolution)

1 free parameter
(no evolution)

Extracting the unpolarized TMD Gaussian widths from SIDIS multiplicities

**In the simplest form
of this model:**

Flavor-independent
average transverse momenta

No x-dependence

No z-dependence

Two parameters in total



Gaussian model:

$$\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle.$$

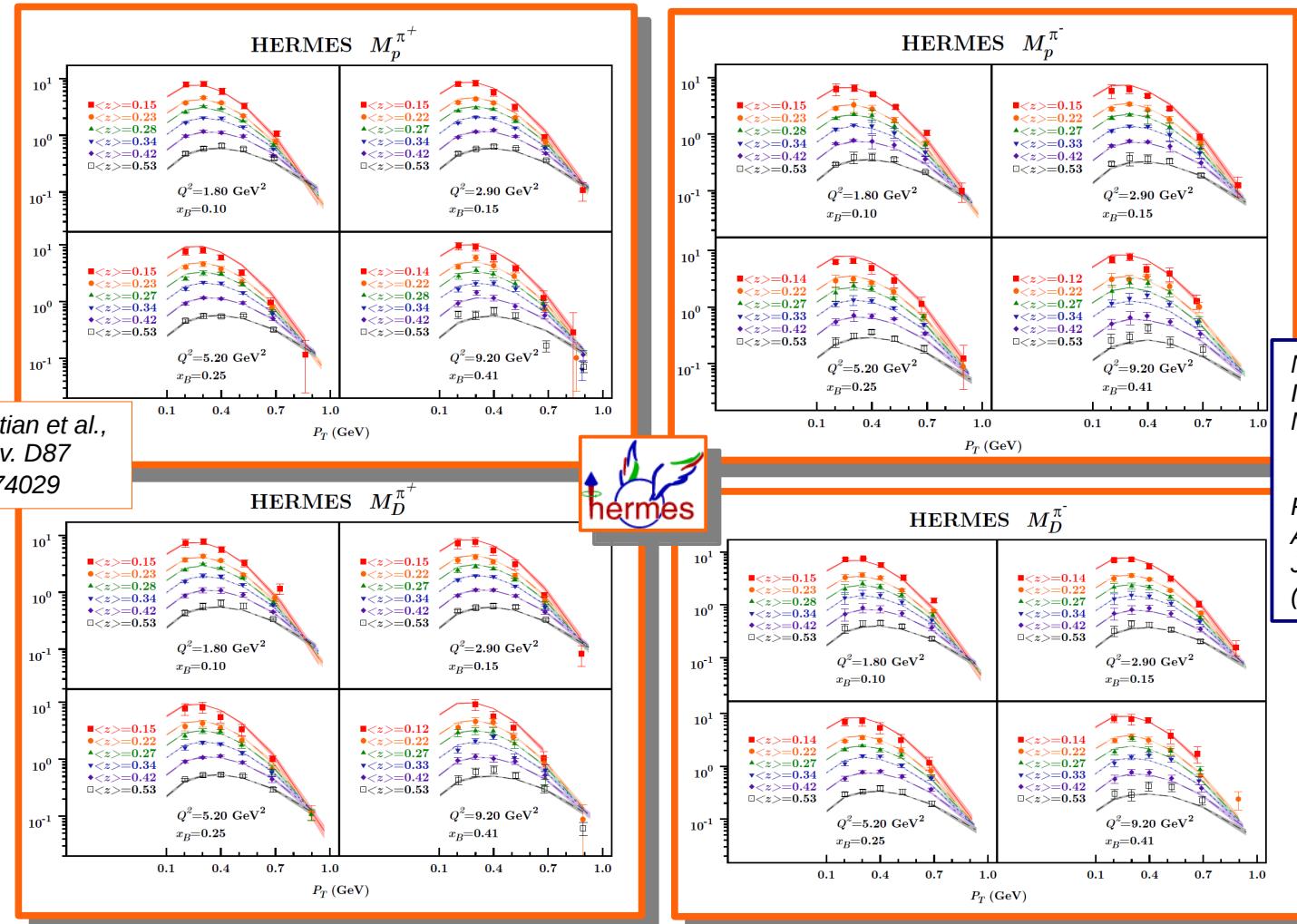
$$\sigma \propto \frac{1}{\pi \langle P_T^2 \rangle} e^{-P_T^2 / \langle P_T^2 \rangle}$$

Normalization

Gaussian width

Extracting the unpolarized TMD Gaussian widths from SIDIS multiplicities

M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261



A. Airapetian et al.,
Phys. Rev. D87
(2013) 074029

Our cuts:

$$Q^2 > 1.6 \text{ GeV}^2$$

$$z < 0.6$$

$$0.2 < P_T < 0.9$$

NO flavour dep.
In distr. fns.,
MILD flavour dep.
in fragm. fns,

Results agree with
A. Signori et al.,
JHEP 1311
(2013) 194

$$\langle k_\perp^2 \rangle = 0.57 \pm 0.08 \text{ GeV}^2$$

$$\langle p_\perp^2 \rangle = 0.12 \pm 0.01 \text{ GeV}^2$$

$$\chi_{\text{dof}}^2 = 1.69$$

Extracting the unpolarized TMD Gaussian widths from SIDIS multiplicities

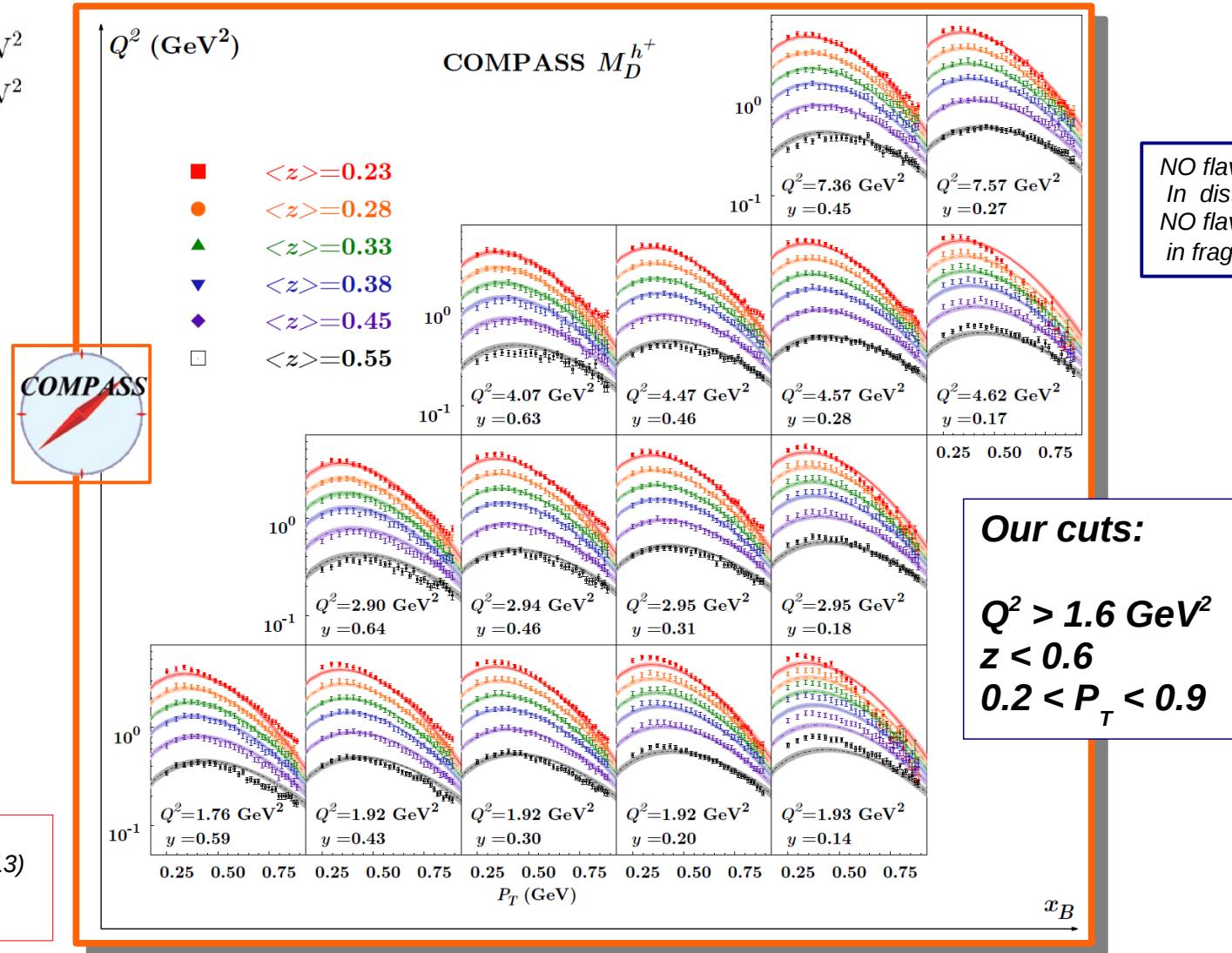
M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261

$$\langle k_\perp^2 \rangle = 0.60 \pm 0.14 \text{ GeV}^2$$

$$\langle p_\perp^2 \rangle = 0.20 \pm 0.02 \text{ GeV}^2$$

$$\chi_{\text{dof}}^2 = 3.42$$

$$N_y = A + B y$$

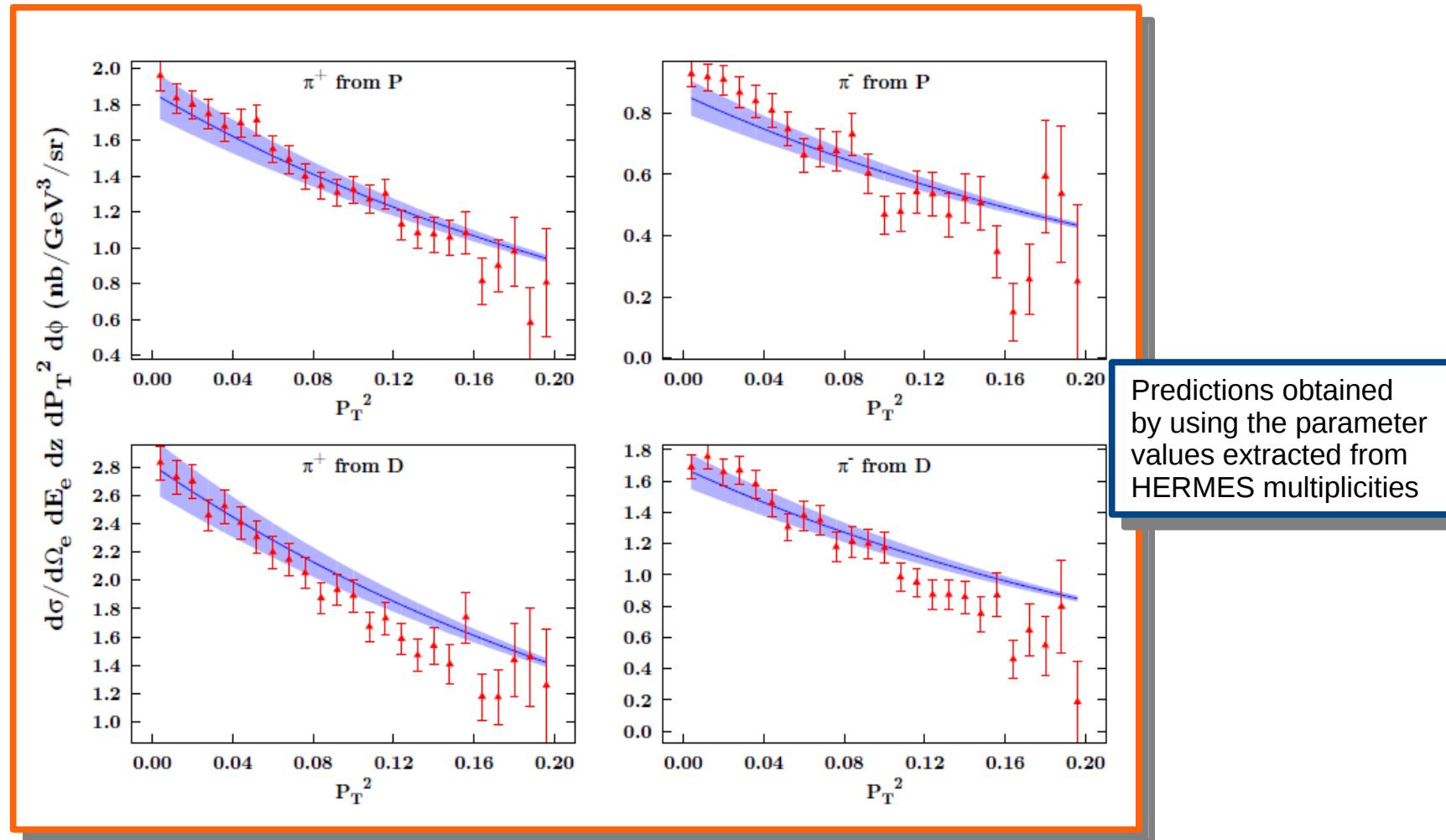


C. Adolph et al.,
Eur. Phys. J. C73, 2531 (2013)
 Erratum: *Eur. Phys. J.* C75
 (2015) no. 2, 94

***Now compare with measurements
from different experiments ...***

Comparison with Jlab 6 data HALL C

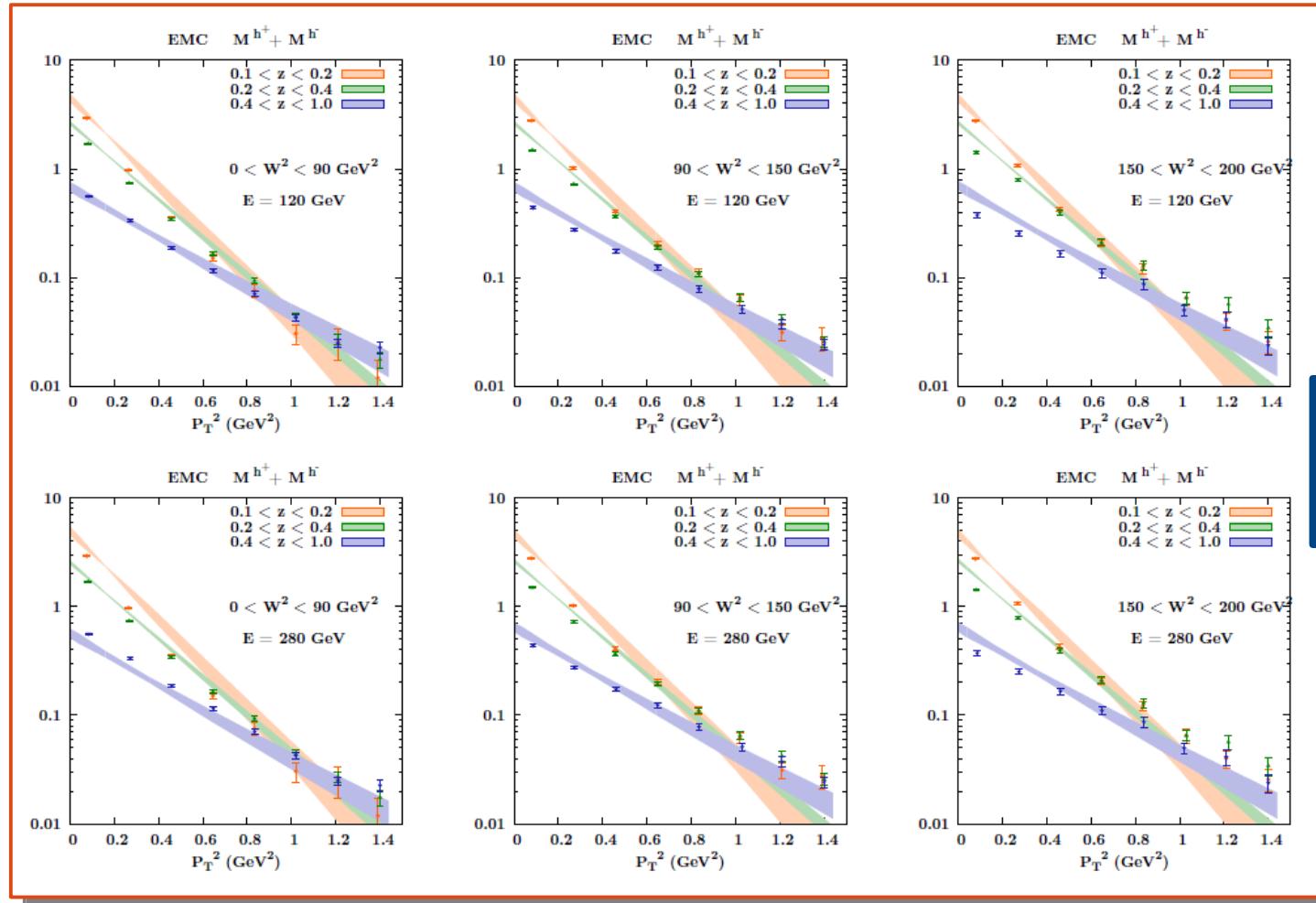
M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261



R. Asaturyan et al., Phys. Rev. C85, 015202 (2012)

Comparison with EMC data

M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261



Predictions obtained by using the parameter values extracted from COMPASS multiplicities

J. Ashman et al. (European Muon Collaboration) Z. Phys. C52, 361 (1991)

Contributions from an EIC

- This results are obtained by assuming that the widths of the k_\perp and p_\perp distributions are flavour independent and constant.
Only two free parameters in the fit: $\langle k_\perp^2 \rangle$ and $\langle p_\perp^2 \rangle$.

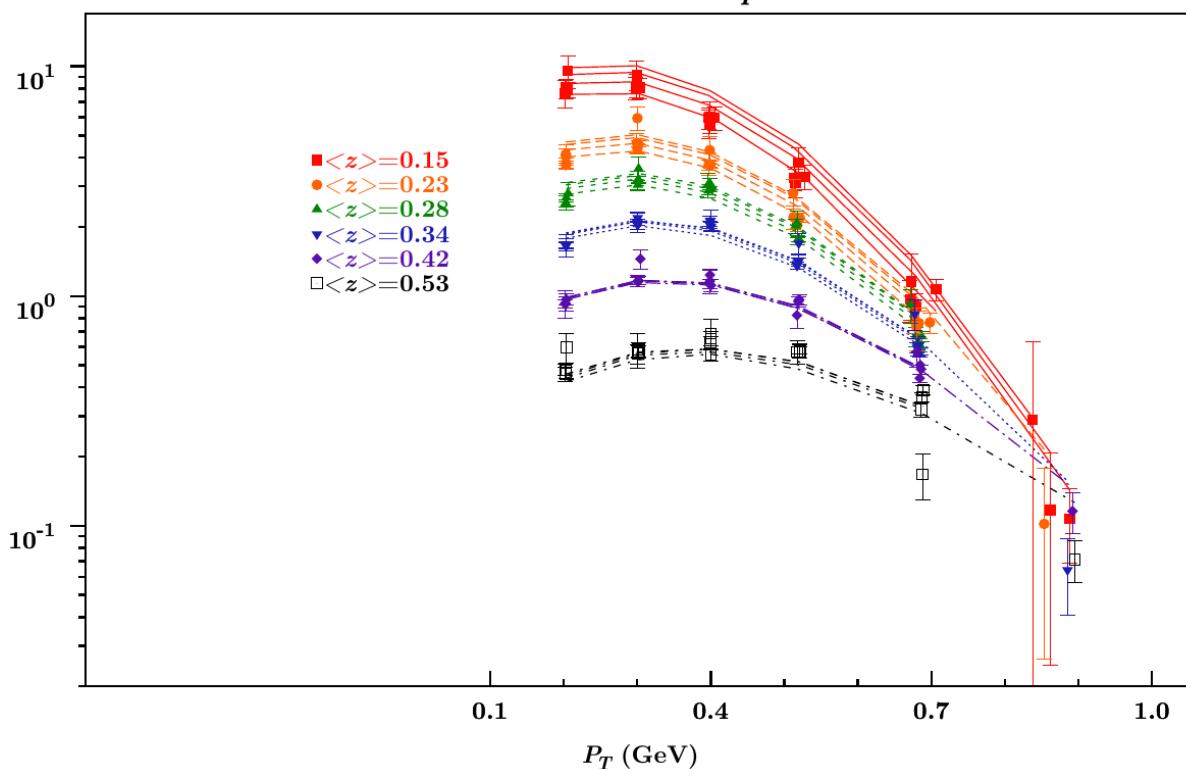
No distinction between valence (u and d) and sea contributions, no dependence of $\langle k_\perp^2 \rangle$ and $\langle p_\perp^2 \rangle$ on x and z.

EIC will help achieving better knowledge of the sea TMDs at lower x values, where they are expected to be large and dominant.

Q^2 dependence of HERMES data...

$$F_{UU} = \sum_q e_q^2 f_{q/p}(x_B) D_{h/q}(z_h) \frac{e^{-P_T^2/\langle P_T^2 \rangle}}{\pi \langle P_T^2 \rangle}$$

HERMES $M_p^{\pi^+}$



Anselmino et al. JHEP 1404 (2014) 005

$$\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle$$

$$\langle k_\perp^2 \rangle = 0.57 \pm 0.08 \text{ GeV}^2$$

$$\langle p_\perp^2 \rangle = 0.12 \pm 0.01 \text{ GeV}^2$$

$$\chi^2_{\text{dof}} = 1.69$$

All four bins have been overlapped in the same panel

Hard to decouple the Q^2 dependence from HERMES data alone

Scale Evolution of unpolarized multiplicities

HERMES and COMPASS multiplicities cover the same range in Q^2 ...

$$\langle k_\perp^2 \rangle = g_1 + g_2 \ln(Q^2/Q_0^2) + g_3 \ln(10 e x)$$

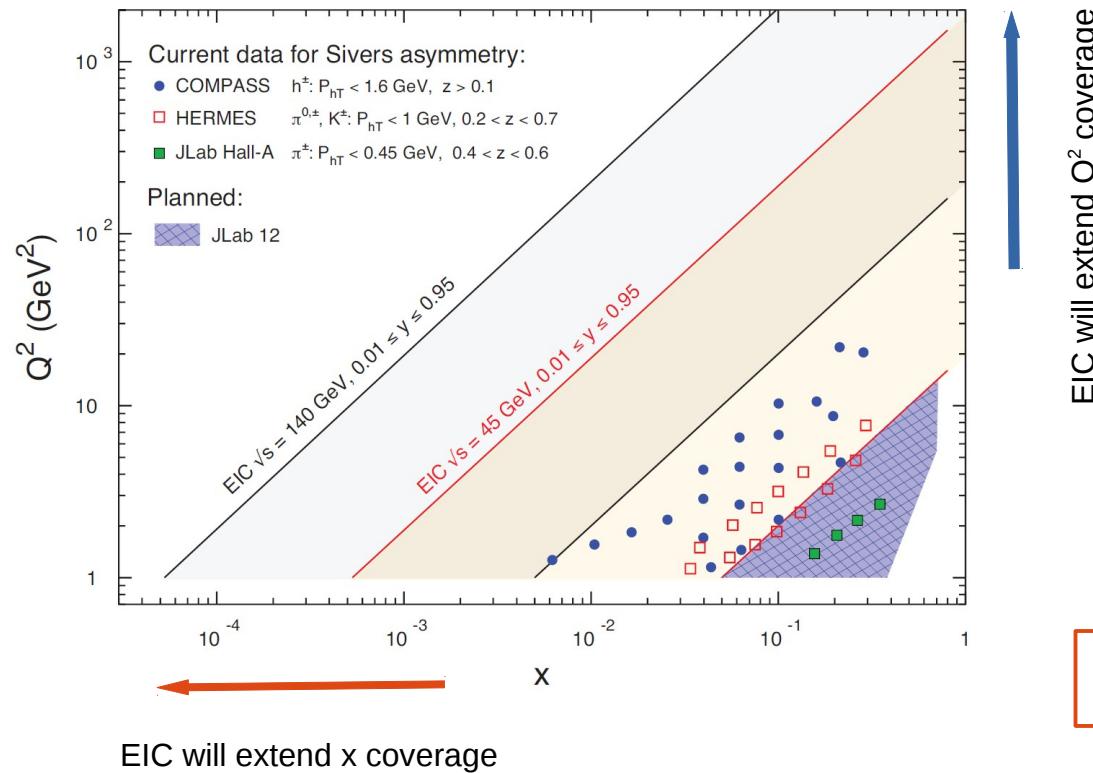
$$\langle p_\perp^2 \rangle = g'_1 + z^2 g'_2 \ln(Q^2/Q_0^2)$$

$$\langle P_T^2 \rangle = g'_1 + z^2 [g_1 + g_2 \ln(Q^2/Q_0^2) + g_3 \ln(10 e x)]$$

- HERMES multiplicities show no sensitivity to these parameters
- COMPASS fitting is much more involved.
After correcting for normalization,
we find that the total χ^2 decreases from 3.42 to 2.69.
- New COMPASS data on P_T dependent multiplicities will help
- **EIC data on P_T distribution will greatly improve our understanding of TMD evolution**

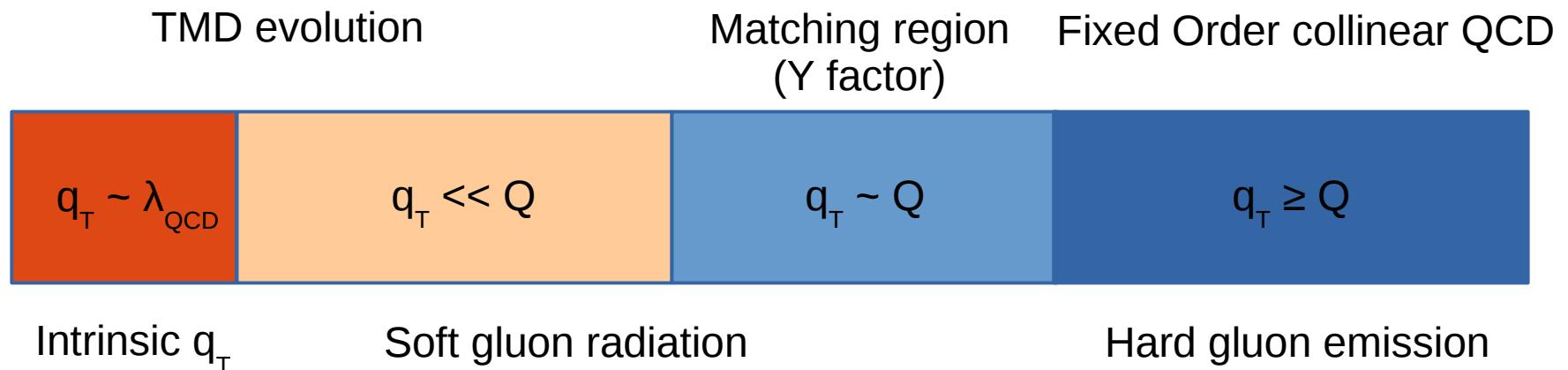
Scale Evolution of unpolarized multiplicities

- HERMES and COMPASS multiplicities cover quite limited (and very similar) ranges in Q^2
- EIC will extend the coverage in Q^2 , helping us to understand TMD evolution



TMD regions

- For this scheme to work, 4 distinct kinematic regions have to be identified
- They should be large enough and well separated

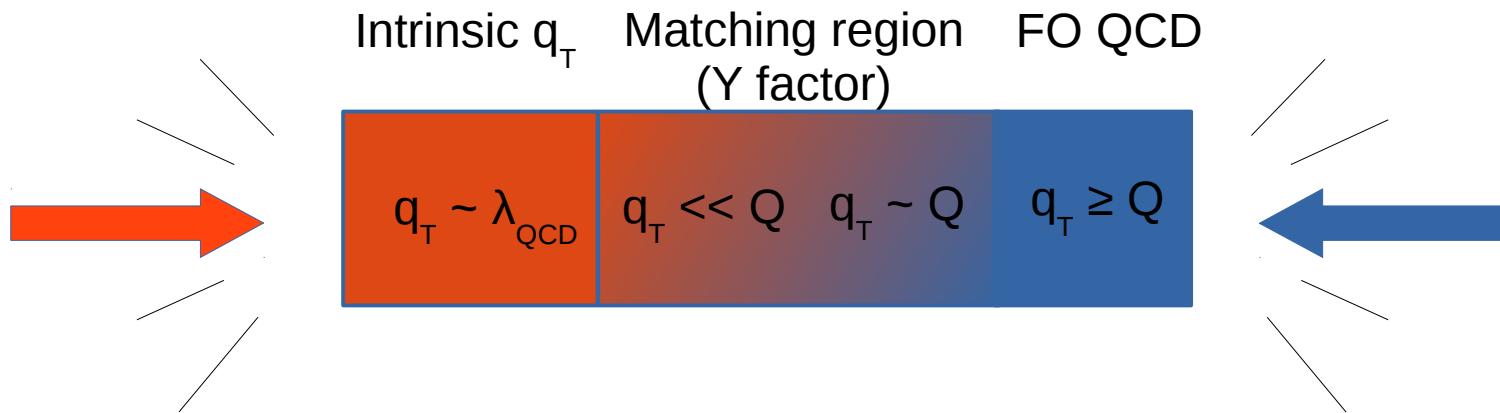


TMD regions

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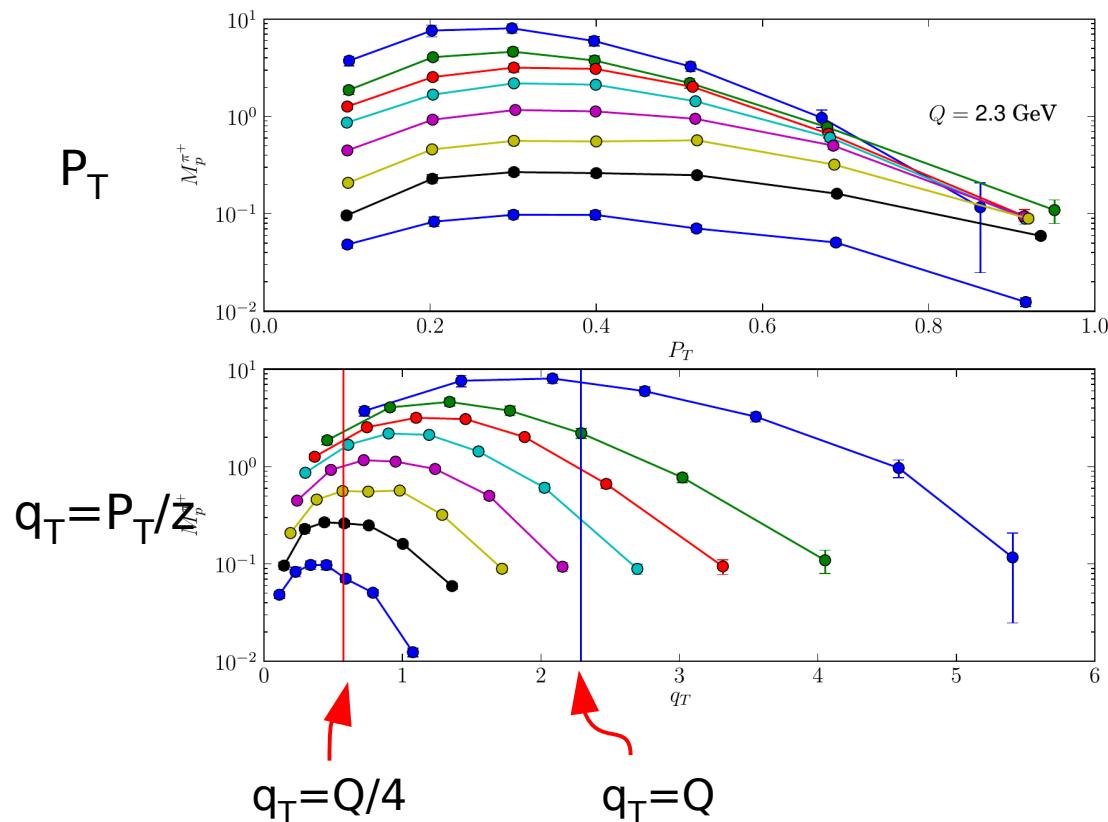
Does not work in SIDIS !

TMD evolution



TMD regions

TMD regions are defined in terms of q_T , however $P_T = zq_T$ is the natural variable for SIDIS



TMD regions

- Which is the right criterion for data selection ?
- How do we put cuts on transverse momentum ?
- How do we define the “current fragmentation” region ?

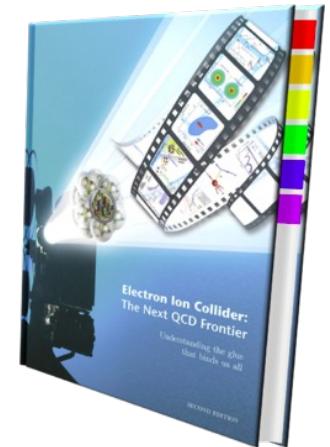
J. Collins, M. Boglione, L. Gamberg, O. Gonzalez, T. Rogers, N. Sato, work in progress ...

*See talk by
Osvaldo Gonzalez,
later on today in
Parallel Session 6A*

Summary

- Naive TMD Models can describe HERMES data
- Similarly to DY the Q^2 dependence is not clearly visible in the shape of the spectrum
- TMD resummation is difficult
 - ✖ no information on TMD fragmentations
 - ✖ issues with normalization
 - ✖ in SIDIS most of the data is at intermediate q_T , however both q_T and Q are small compared to DY processes the non-perturbative behavior is dominant

EIC will explore a broader range in PT / qT and shed light on the transition between perturbative (Collinear factorization) and non-perturbative (TMD factorization) ranges.



Polarized TMDs ...

The Sivers function

Exploring the proton Sivers sea

Anselmino, Boglione, D'Alesio, Murgia, Prokudin, in preparation ...

- A new Sivers fit has recently been performed, motivated by the necessity to explore the sea contributions in a more detailed way.
- In this fit the Sivers function depends on Q through its collinear part, which evolves according to DGLAP equations. No TMD evolution is considered.
- This fit is based on a different parametrization of the sea Sivers functions, in which we assume them to be directly proportional to their unpolarized counterparts:

$$\Delta^N f_{q/p^\dagger}(x, Q_0) = 2 \mathcal{N}_q(x) f_{q/p}(x, Q_0)$$

Previous fits

$$\mathcal{N}_q(x) = N_q x^{\alpha_q} (1-x)^{\beta_q} \frac{(\alpha_q + \beta_q)^{(\alpha_q + \beta_q)}}{\alpha_q^{\alpha_q} \beta_q^{\beta_q}}$$

Same for valence and sea contributions

New fit

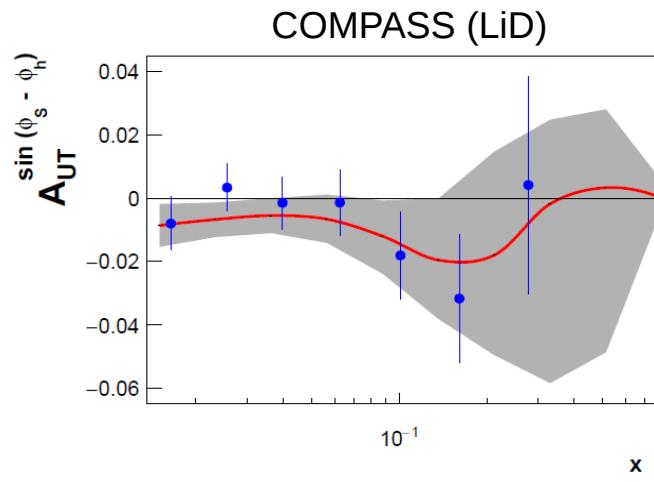
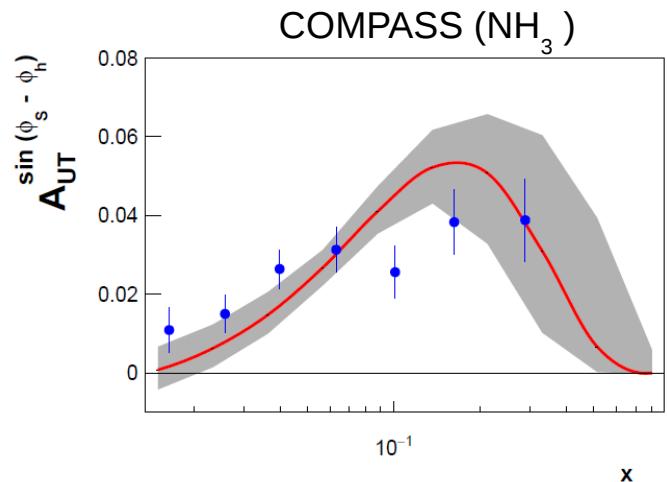
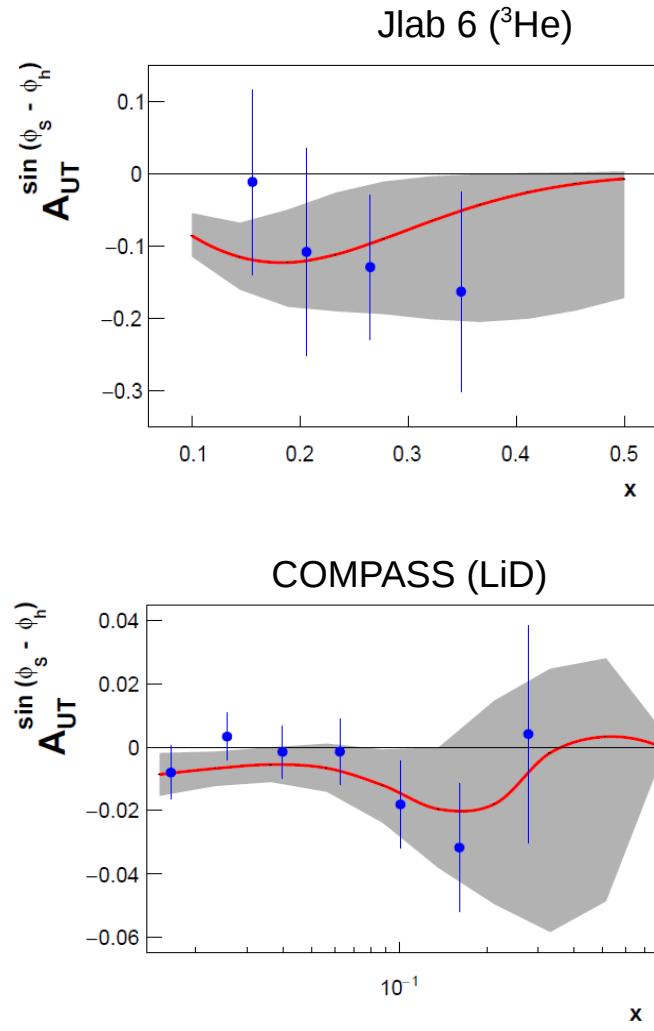
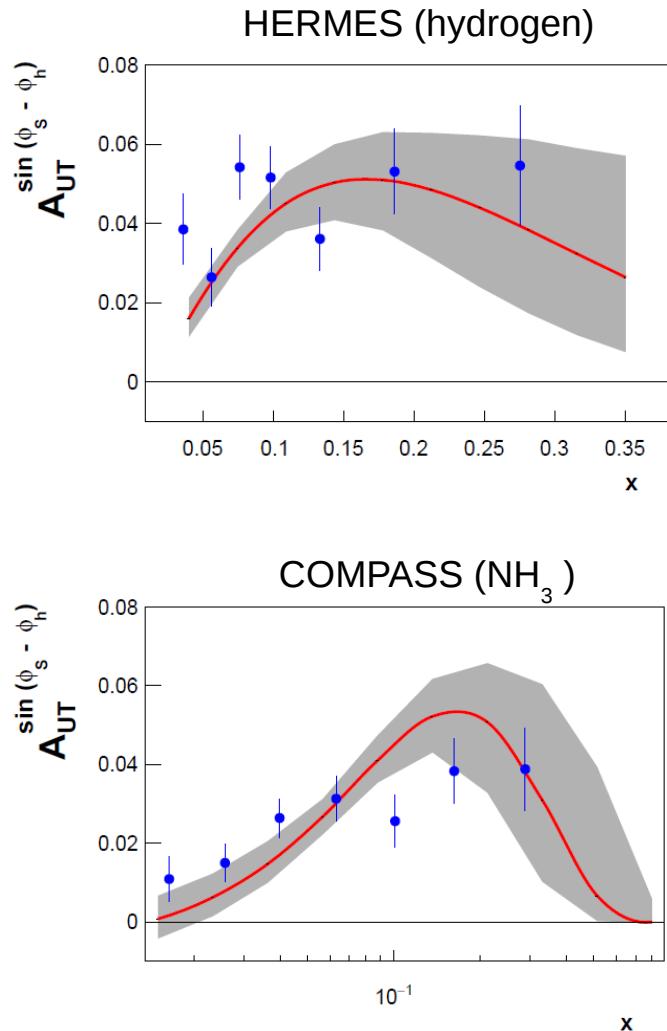
$$\mathcal{N}_q(x) = N_q x^{\alpha_q} (1-x)^{\beta_q} \frac{(\alpha_q + \beta_q)^{(\alpha_q + \beta_q)}}{\alpha_q^{\alpha_q} \beta_q^{\beta_q}}$$

$$\mathcal{N}_{\bar{q}}(x) = N_{\bar{q}}$$

- HERMES (hydrogen target), COMPASS (NH_3 and LiD targets) and JLAB (${}^3\text{He}$ target) SIDIS data are fitted

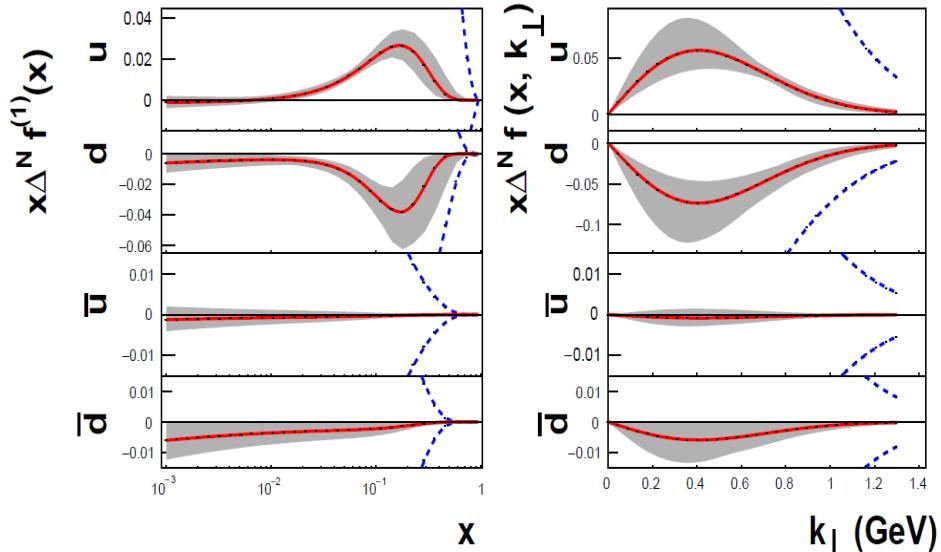
New Sivers fit

Anselmino, Boglione, D'Alesio, Murgia, Prokudin, in preparation ...

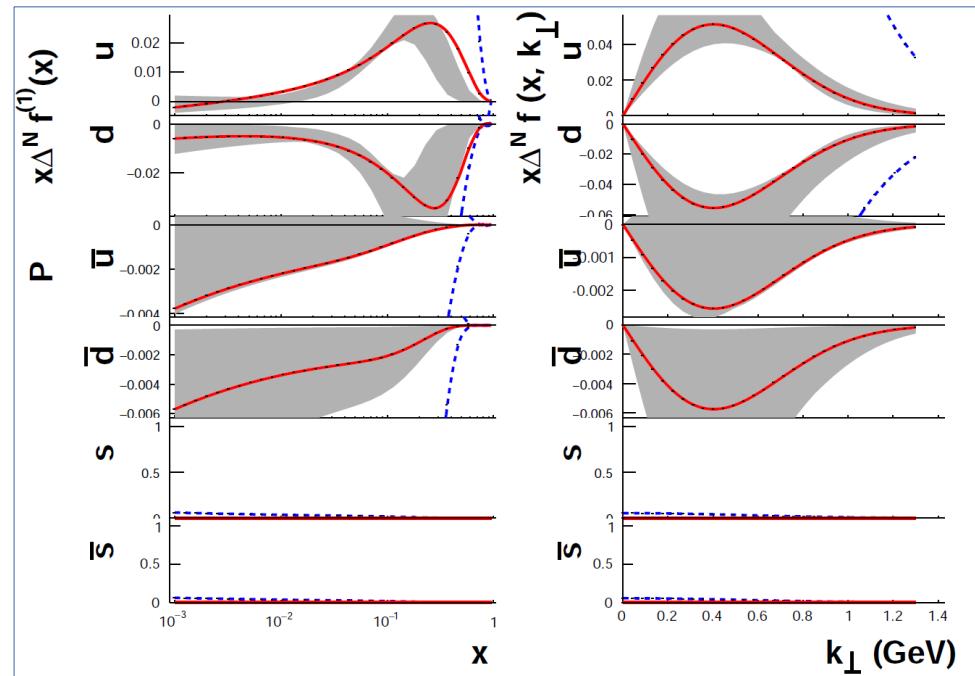


New Sivers fit

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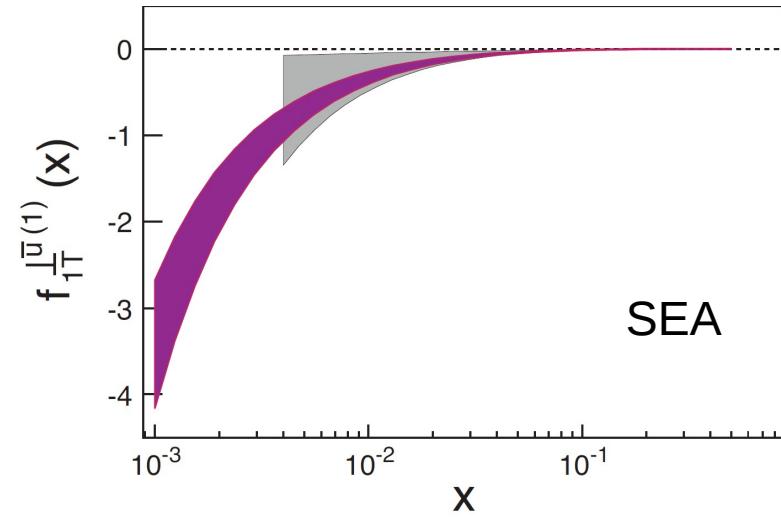
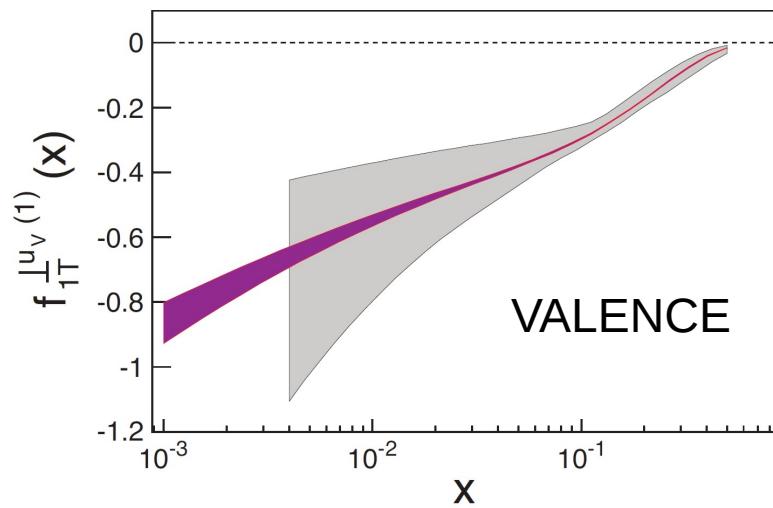


- Strong dependence of the sea Sivers function on the chosen parametrization



- The Sivers sea is affected by large uncertainties
- The \bar{d} contribution to the Sivers function is negative and has definite sign, while the \bar{u} contribution is (presumably) small and has no definite sign.

- EIC measurements will help improving our knowledge on the low- x behaviour of unpolarized and polarized TMDs, where sea contributions are expected to be large and dominant



Plots by A. Prokudin
from the EIC white book

Polarized TMDs ...

**Simultaneous extraction
of transversity and the
Collins function**

*See talk by
Alexei Prokudin,
later on today in
Parallel Session 4A*

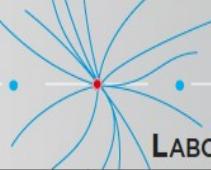
Outlook and Conclusions

- We are now ready to enter a new phase of high precision studies of TMDs
- Need cross section or multiplicity data to extract unpolarized PDF and FF TMDs
 - ★ Drell Yan studies show that the cross section can be well reproduced over a very wide (full) q_T range
 - ★ SIDIS studies are presently being performed including TMD evolution and resummation – issues with matching and Y factor
 - ★ Global analyses of SIDIS and e^+e^- high statistics and high precision new data sets deliver very satisfactory results, although they seem to be little sensitive to TMD evolution effects.
- **EIC will extend our knowledge of TMDs over a much wider range in Q^2 (higher resolution) and shed light on TMD factorization.**
- **EIC will extend our knowledge of TMDs over a wider low- x range, and shed light on the TMD sea.**

Transversity 2017 in Frascati (ROMA) Italy !!!



Istituto Nazionale
di Fisica Nucleare



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TRANSVERSITY 2017

11 December 2017 @ 8:00 - 15 December 2017 @ 18:00

The main aim of the Workshop is to get together theorists and experimentalists engaged in investigating the nature of transverse spin in hadron physics, to exchange up-to-date theoretical and experimental ideas, news and perspectives on the subject.

The Workshop follows the successful editions held in :

- 2005 on Lake Como (Italy)
- 2008 Ferrara (Italy)
- 2011 in Losinj (Croatia)
- 2014 Cagliari (Italy).

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati



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